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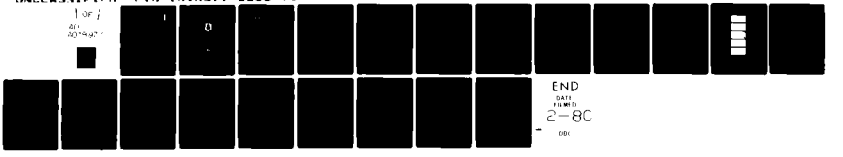

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AN ANALYSIS OF THE PARAMETERS OF A GAS-DYNAMIC LASER WITH THE ACETYLENE COMBUSTION

By

Michal Syczewski

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AN ANALYSIS OF THE PARAMETERS OF A GAS-DYNAMIC LASER WITH THE ACETYLENE COMBUSTION

PART I. THE INFLUENCE OF PRESSURE ON THE LASER PARAMETERS

MICHAL SYCZEWSKI
Military Technical Academy, Warsaw

The effect of decompression of gases (the ratio of pressure on the vacuum side - p, to the maximum pressure in the combustion chamber - $p_{s\,max}$) on the impulse radiation energy of a laser was investigated. Interpretation of the results was carried out on the basis of the recorded curves of the impulse power for characteristic values of the ratio $p/p_{s\,max}$ as a function of time, and on the basis of theoretical calculations of the parameters of gases in the resonance cavity.

Reference /1/ describes the research setup of a gas-dynamic laser with utilization of heat and combustion products of acetylene. In subsequent stage, the laser was improved and systematic studies on optimization of the conditions of its work were started.

Following the suggestion in /1/, in the present series of experiments we used an improved composition of outlet gases - which this time contained carbon dioxide in addition to acetylene and air. This was achieved by lowering the temperature of the products of combustion while maintaining the optimal number of the working CO_2 molecules.

The aim of this work was to investigate the influence of the conditions of gas flow on the impulse energy of laser.

The conditions of flow were varied by changing the ratio of pressure in the vacuum tank to pressure in the combustion chamber.

Results of investigations of this type of lasers, published so far /2/, deal usually with the dependence of energy (or part of the coefficient of radiation enhancement) on the so-called inhibiting parameters, i.e., parameters (temperature and pressure) in the combustion chamber. Often they neglect the fact that in a gas-dynamic laser with impulse action the conditions of gas flow are changing during the impulse. Consequently, at every moment of the duration of impulse there are different pressures both in the combustion chamber and in the vacuum reservoir.

The shape of the nozzle used in practice ensures optimal conditions of gas flow for only one value of the ratio of pressure in vacuum tank to pressure in the combustion chamber. Only at this particular value of the ratio, gases in the nozzle undergo decompression to the value of pressure governing in the vacuum tank, and the gas stream at outlet of the nozzle (in diverging part) is a unidirectional stream, without turbulance.

Throughout most of the time of the duration of impulse there is either insufficient or excessive decompression of gases. Hence the flow is no longer unidirectional.

In this work we are trying to discuss these problems on the basis of results obtained on an experimental setup described in detail in the work /1/.

Experimental conditions

The main part of the laser consists of a combustion chamber with a flat, gap-type nozzle connected to a vacuum chamber /1/. In the supersonic part, across the stream of flowing gases, there is placed the resonance cavity of the laser (the length of active part 20 cm). The resonator in the present series of experiments consisted of a totally-reflecting aluminum mirror with the radius of curvature 104 cm, and a semitransparent mirror coated with gold on germanium base. The transmission of this mirror was ensured by a dot not covered with gold, of diameter 5 mm. Taking into consideration the reflection from the polished non-covered part of the surface of germanium, the total transmission was about 3% (no optimization of resonator was done).

The nozzle was diverging to the outlet in the profile way, and not in the form of a wedge. The maximal at the beginning half-angle of divergence was about 40°.

In lasers of this type, i.e. of semicontinuous action, the most important parameter is the energy of the whole radiation impulse of the laser. The energy was measured by a calorimetric energy meter. When studying the effect of a given parameter on the radiation impulse energy of laser, utmost care was taken to preserve the remaining parameters (nozzle construction, resonator, etc.) unchanged.

The main effort in this work was directed to study of the influence of the degree of decompression of gases (P/P_{max}) on the radiation impulse energy of the laser E .

Results of measurements and their interpretation

Figure 1 shows the relation $E=f(p/p_{s\max})$, where: p - pressure in vacuum chamber (average), $p_{s\max}$ - maximum pressure in combustion chamber (approximately constant and equal to 2.12×10^6 N/m^2). The ratio of pressures was changed mainly through the change of pressure on the vacuum side, from 533 N/m^2 to about 2.666×10^4 N/m^2. The curve of the relation $E=f(p/p_{s\max})$ exhibits a distinct maximum at the value of ratio of about 10^{-3}.

To facilitate the interpretation of results, Figure 2 shows the optimal value of the ratio of cross-section surfaces of the nozzle A_{kr}/A and values of the ratio of temperatures T/T_s (T - temperature of gases after decompression, T_s - temperature of gases in the combustion chamber) as a function of the ratio of pressures p/p_s. The curve $A_{kr}/A=f(p/p_s)$ was determined from the relation:

$$\frac{A_{kr}}{A}=\frac{(p/p_s)^{1/k}}{\left(\frac{2}{k+1}\right)^{(k+1)/2(k-1)}}\sqrt{\frac{1-(p/p_s)^{k-1/k}}{\frac{k-1}{2}}} \qquad (1)$$

and the ratio of temperatures from the adiabatic relation:

$$\frac{T}{T_s}=(p/p_s)^{k-1/k} \qquad (2)$$

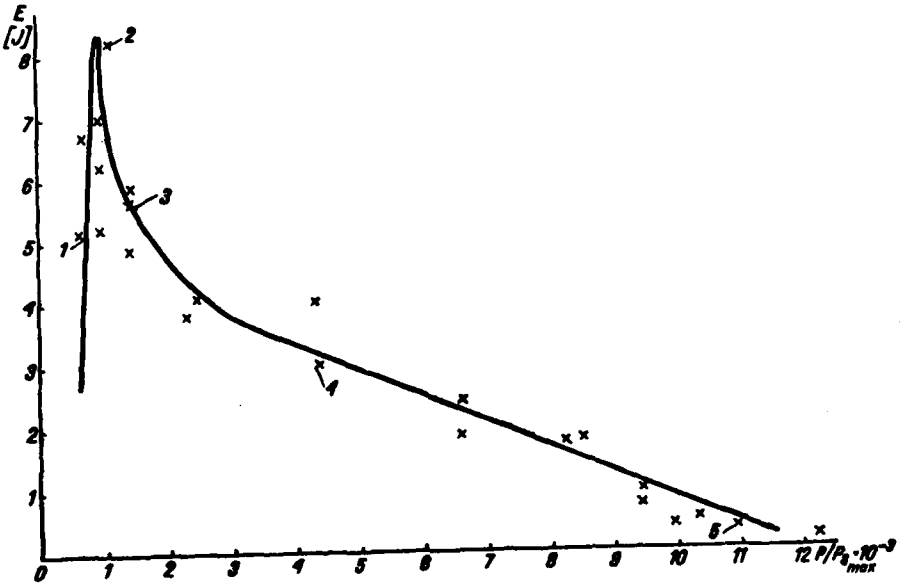

Figure 1. Dependence of the impulse energy of laser on the ratio of pressure in the vacuum chamber p to the maximum pressure in the combustion chamber $p_{s\,max}$. Measurements were made of changes in the laser impulse and pressure with time for points 1-5 (Figure 3).

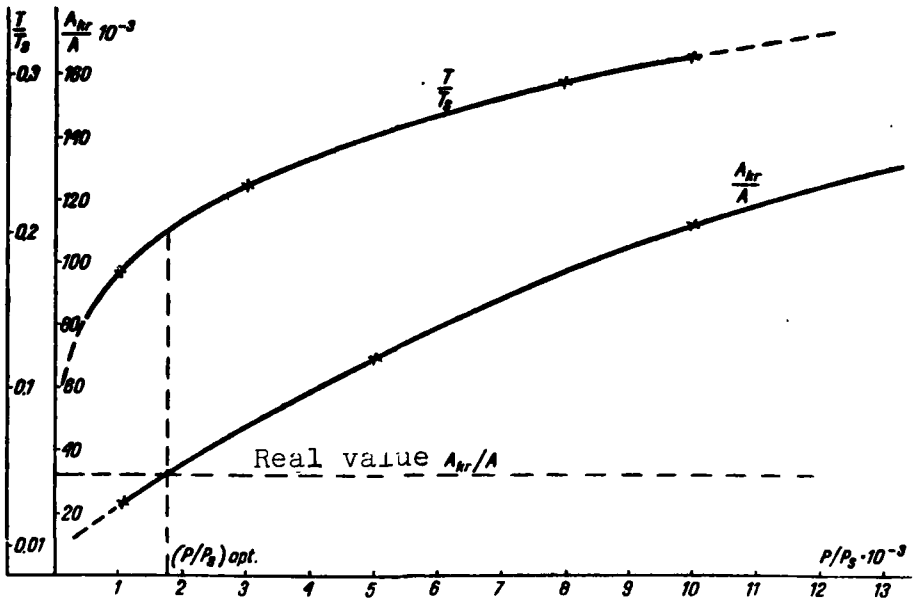

Figure 2. Dependence of the optimal ratio of the cross-section areas of the nozzle A_{kr}/A and of the ratio of temperatures T/T_s on the ratio of pressures P/P_s.

A_{kr} - critical cross-section of the nozzle,

A - cross-section at the outlet of the nozzle,

T - temperature at the outlet of the nozzle,

T_s - temperature in the combustion chamber.

The average value of the adiabatic coefficient k (for the given-below composition of the products of combustion) was assumed to be $k = 1.34$.

The nozzle used in practice ensured the optimal conditions of the gas flow for only one value $p/p_s=(p/p_s)_{opt}$. In Figure 1 to the right of this value, through the whole working cycle, there was an excessive decompression of gases in the nozzle. This could result in separation of wall-adjacent layers and in formation of the standing wave of the pressure drop inside the nozzle.

To the left of $(p/p_s)_{opt}$ there is an insufficient decompression of gases, beginning from $p_s=p_{s\,max}$ up to the moment when the varying value of p_s satisfies the condition $p/p_s=(p/p_s)_{opt}$. In this area of pressures (Figure 1) there is always a moment of the work of laser when the the optimal gas-dynamic conditions of flow of the stream of gases are fulfilled.

The course of the impulse radiation of laser and of pressure in the combustion chamber with time was measured for characteristic points on the curve - denoted by 1-5 in Figure 1. Figure 3 shows oscillograms of these measurements. Along the curves of pressure the oscillograms show a scale of time (1 division = 0.05 sec).

Remembering that in the presented investigations (Figure 1) the change of $p/p_{s\,max}$ was effected mainly through the change of pressure on the vacuum side ($p_{s\,max}$ in the majority of cases amounted to about 21 atm), we can read from the graph an approximate value of the maximal pressure in the vacuum chamber at which the generation

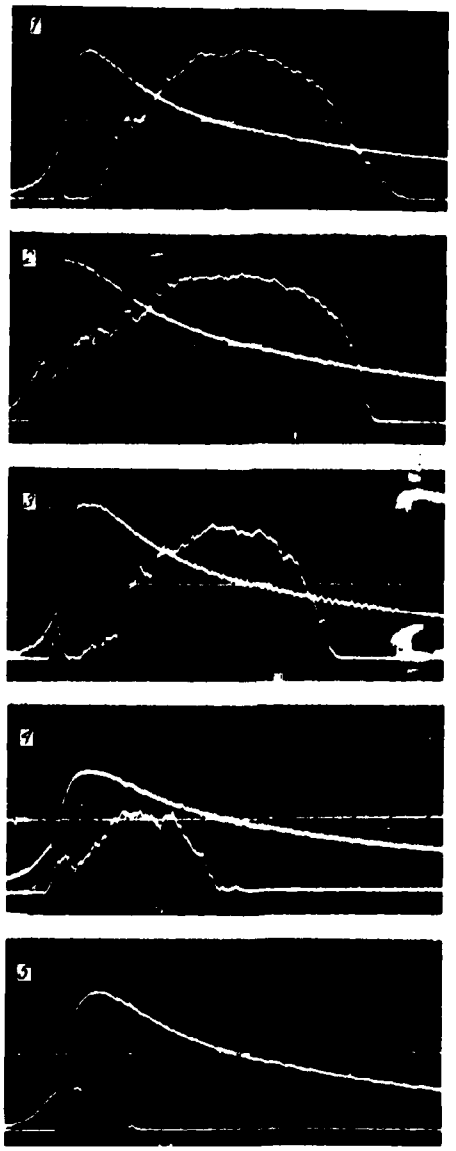

Figure 3. The curves of pressure and laser impulse for characteristic points corresponding to specific ratios of pressures of the work of laser (denoted as in Figure 1).

of laser radiation ceases. For the given conditions of the nozzle and resonator this value is about 2.666×10^4 N/m^2 (200 mm Hg). It has to be pointed out that an increase of pressure in the combustion chamber has no real effect on shifting of this limit towards higher pressures in the vacuum chamber.

It is seen from Figure 3 that in all the cases there is a too early interruption of the generation of radiation. The earliest interruption occurs when the pressure in vacuum chamber is higher. For instance, in the case of the oscillogram 5 the generation ceases when the pressure in combustion chamber is about 17.2×10^5 N/m^2 (17 atm).

The phenomenon of decrease of the radiation energy of laser with an increase of pressure in the resonance cavity is rather obvious. Neglecting the fact that the shape of nozzle is not optimal in this pressure range for the whole time of duration of the laser impulse, the main reason for decrease of the energy of laser is an increase of the rate of deactivating transitions in CO_2 molecules with the rise of pressure and temperature (see the curve T/T_s in Figure 2).

Moving in the direction of lower pressures in the active zone of the resonator we see that the energy of laser impulse increases, despite the fact that the concentration of working CO_2 molecules decreases. We explain it by the fact that the radiation-less relaxation processes decrease faster (because of simultaneous decrease of T and p) than the concentration of molecules /3/. And we get a higher degree of freezing of the population of upper

laser level of CO_2 molecules in the resonance cavity.

Next, we come to such values of the ratio of pressures where an increase of energy is very rapid (point 3 in Figure 1), despite a further drop of pressure in the resonance cavity. Interpretation of the curve in Figure 1 below this value of the ratio of pressures is by no means simple. Comparing the curve $E=f(p/p_s)$ with the curve $T/T_s=f(p/p_s)$ one can notice that this increase of energy occurs in the area where the ratio of temperatures begins to change also more rapidly with decrease of the ratio P/P_s. It follows from the fact that T_s in all experiments is approximately a constant value (the same composition of gases, the same combustion pressure) that the reason for such a rise in energy is a drop of the translational temperature of gases in the area of cavity. There follows then the freezing of the population of upper laser level of CO_2 molecules.

Moreover, this increase of the energy of laser impulse falls in the area of pressures where the applied nozzle has the optimized dimensions from the gas-dynamic aspect. This fact indicates that, in the area of maximal pressure in combustion chamber, gases are decompressed in the resonance cavity to the value of pressure in the vacuum tank, and there is no turbulant flow in the nozzle.

After reaching $p/p_{s\,max}<(p/p_s)_{opt}$ the optimal conditions of the flow of gas stream do not fall at $p_{s\,max}$, but at a lower pressure. Lower parameters of inhibition do not ensure a sufficiently large inversion of the population of CO_2 levels, although there are

the optimal gas-dynamic conditions of flow. Therefore, after lowering the ratio of pressures $p/p_{s\max}$ below 10^{-3} we do not observe any further increase of the energy of radiation impulse of the laser (point 2 in Figure 1). When the ratio of pressures reaches the value below 0.8×10^{-3}, we observe a sudden drop of the impulse energy. As can be seen from oscillogram 1 (Figure 3), a characteristic feature for this range of pressures is the interruption of generation at the beginning of the duration of impulse.

In the first period of the decompression of gases, at a pressure close to $p_{s\max}$, there is a higher pressure in the resonance cavity than in the vacuum reservoir, and this pressure is close to that which exists in experiments when $p/p_{s\max} \approx (p/p_s)_{opt}$. In this connection we should not expect a sudden change (disappearance) of generation conditions because of too low a concentration of active molecules in the resonance cavity. Because of insufficient decompression this concentration is not such as governed by pressure in the vacuum tank (about 666 N/m^2) but corresponds more to pressure in vacuum tank and in resonance cavity at $(p/p_s)_{opt}$. We should consider, therefore, other reasons for decrease of the energy of radiation impulse of laser at low values of pressure in the vacuum chamber and low values of the ratio of pressures. Below we are presenting considerations on the topic of phenomena which could be responsible for the decay of generation in the early period of the duration of impulse.

Considering at first the whole course of impulse, we have to note that at a certain pressure $p_s < p_{max}$ the nozzle works under optimal conditions, and at the end of impulse there is an excessive decompression of gases. In this last period, similarly as in samples 4 and 5 during the whole impulse, there can occur separation of the wall-adjacent layer of gases and the consequent appearance of standing waves of the pressure drop inside the nozzle.

The fact that for $p/p_{s\,max} < 0{,}6 \cdot 10^{-3}$ the energy of radiation impulse of laser decreases rapidly, and that this decrease falls in the area of pressures where T/T_s undergoes a rapid change, suggests that the reason for the drop in the impulse energy could be a phase transition in the products. It appears plausible that there is a moment of the work of laser in which translational temperature in the resonance cavity falls below the temperature of condensation of water. Such a phase transition in the products of combustion could produce the observed sharp changes in the impulse energy.

Taking into consideration the content of water in combustion products as a sum of water formed in the reaction and of water brought in with the substrates (substrates are not dried), we find that its amount reaches about 5%. Under the considered conditions, the total pressure in resonance cavity is about $6{,}665 \cdot 10^2$–$7{,}998 \cdot 10^2$ N/m^2 (5–6 mm Hg), hence the partial pressure of water vapor is about 34.66 N/m^2 (0.26 mm Hg). Under such conditions the state of saturation (beginning of condensation) will be reached at the temperature of about 240 K. We shall consider below whether gases in resonance

cavity can reach such a state.

On the basis of recorded maximal pressure in combustion chamber, calculations were made for composition of the products of combustion and for temperature of gases /4/. The equation for the combustion reaction, per one mole of acetylene, has the form:

$$C_2H_2 + 3{,}25O_2 + 14N_2 + 2{,}9CO_2 = 4{,}851\,CO_2 + 0{,}049\,CO + H_2O + 14N_2 + 0{,}774O_2$$

The number of moles of substrates n_0 = 21.15, the number of moles of products n = 20.675, the combustion temperature T_s = 2250 K. Having these data, and utilizing the adiabatic equation (2), we can calculate the approximate temperature in the resonance cavity. The required value of adiabatic coefficient was determined from the above given composition of products for the temperature 273 K (and not for 600 K as at T/T_s in Figure 2). In this case, the value of the coefficient is k = 1.38. The translational temperature in resonance cavity, calculated for this value, is T = 298 K. In calculations we assumed the value $p/p_s = 0.65 \times 10^{-3}$, the value at which the impulse energy of laser is clearly lower than the maximal one. Taking into consideration that the flow of gases through the nozzle begins before reaching the maximal pressure, we see that at p_{max} the combustion reaction does not reach the equilibrium state. Hence, at that moment the temperature of the products of combustion does not reach in practice the calculated value. The pressure ceases to rise not because of the completion

of reaction but because of the counterbalancing of the rise of pressure arising from combustion and the fall of pressure arising from the outflow of gases through the nozzle. Rough calculations indicate that temperature of the condensation of water is reached when the temperature in combustion chamber is about 1800 K. Such a temperature in combustion chamber is possible, at the start of the gas flow (when the channel is opened) and at $p_{s\,max}$.

The discussed phenomena, i.e., a lowering of the translational temperature and non-optimal gas-dynamic conditions at $p_{s\,max}$, can jointly cause the complete decay of generation in the initial period of the outflow of gases at $p_{s\,max}$ (oscillogram 1 in Figure 3). This decay of generation at the beginning accounts for the rapid decrease of the total impulse energy of laser at very low ratios p/p_s (Figure 1). The phenomena described above are very sensitive to minimal changes of experimental conditions (sharp dependence $T/T_s = f(p/p_s)$), hence in this range of the ratio of pressures one observes large variations of the values of energy in consecutive experiments.

It seems obvious that the obtained results are valid with respect to values of particular parameters for the given gas-dynamic conditions and for the given shape of nozzle. At other values of A_{kr}/A, the ratio of pressures $(p/p_s)_{opt}$ will lie in different range, and E_{max} will be found in different place, at a different value of p/p_s.

General conclusions

The obtained results and their interpretation diverge somewhat from the results of studies by other authors /2/. So far, no optimal conditions of work for this type of lasers of periodic action were sought because of the magnitude of the total impulse energy, which depends on the power and duration time of the generation. So far, no fact was considered that a laser of this type works through the major part of the duration of impulse under nonoptimal gas-dynamic conditions of flow. The ratio of pressures changes during the impulse while the dimensions of nozzle remain the same.

The premature decay of generation at excessively high pressures in combustion chamber, observed in our case (Figure 3), may be caused by too high a temperature in the area of cavity and by creation of the optical nonhomogeneity of gases because of the formation of standing waves in the cavity region. The excessively high temperature could arise, among others, from the fact that at the time of generation the gases are heated also by final stages of combustion reaction, which were not yet completed before the opening of combustion chamber. If we assume that, because of these residual reactions, the temperature of gases remains at the level of calculated temperature, despite the drop of pressure, then the temperature in resonance cavity at the end of impulse will be about 600 K.

It follows from the above that, in order to utilize better the energy of combustion, the experiments should be carried out in such a way that before the opening of the nozzle the reaction of combustion reaches the state of chemical equilibrium. Also, the shape of the nozzle should ensure the optimal conditions of flow at the maximum pressure in combustion chamber. Under such conditions, gases at the beginning of decompression will be heated to a sufficiently high temperature so that after decompression the temperature will be nowhere near the condensation temperature of water. On the other hand, at the end of the process of decompression the temperature in combustion chamber, because of the drop of pressure, will be lower than the calculated one (main reactions of combustion are completed). Hence, even at a lower degree of decompression the temperature in resonance cavity will not be too high. The value of the product $p\tau$ (τ - lifetime of the 00^01 state of CO_2 molecule) will be sufficiently high /3/ to ensure that, even at higher pressures in the area of cavity, we still obtain the appropriate inversion of populations of the working levels of CO_2 molecule.

This approach to experimental studies, where the optimal conditions of the work of laser were established not only as a function of parameters in combustion chamber (T_s and p_s) but as a function of the degree of decompression, mainly with a change of pressure at outlet from the nozzle, supplements the results published so far /2/ to a substantial degree. Conclusions resulting

from these studies can be adapted to systems with other parameters of the nozzle and resonator. One can utilize then the existing theoretical work dealing with optimization of nozzles and resonator /5/.

Manuscript received in April 1976.

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Summary

The impulse power of a gas-dynamic laser, based on acetylene combustion reaction, was measured as a function of pressure $p/p_{s\max}$, where p is the presuure in the vacuum chamber and $p_{s\max}$ the maximum pressure in the combustion chamber. The ratio $p/p_{s\max}$ was varied maintly by changing p inside the vacuum chamber. The dependence of the power impulse on $p/p_{s\max}$ was obtained in the form of a curve, which is non-monotonic and has a maximum for a certain $p_{s\max}$ value. A record of the laser power as a function of the time was obtained at characteristic points of the curve.

Interpretation of the results obtained leads to practical conclusions as to the optimum conditions for the operation of this type of laser.

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